Non-Gaussian fluctuations in relativistic heavy ion collisions

Masakiyo Kitazawa

一本の草も涼風宿りけり

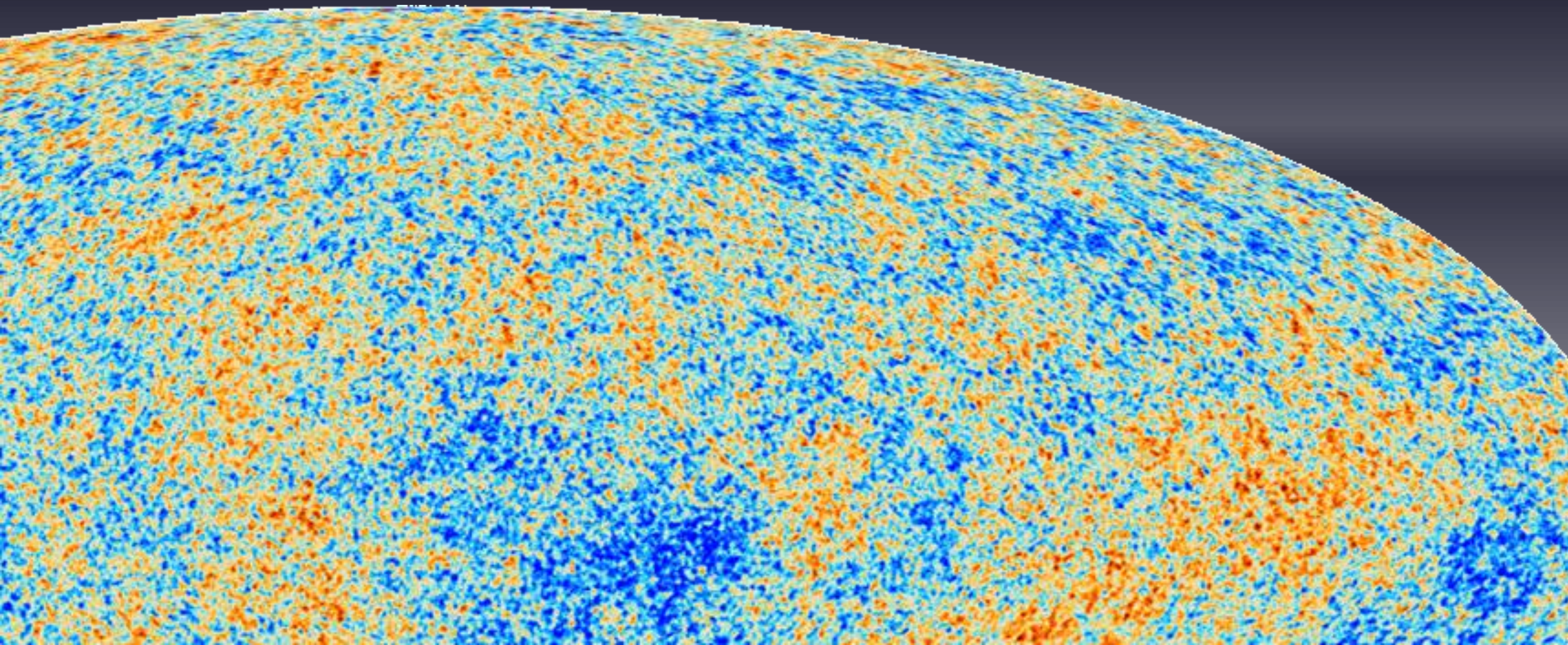
even on one blade of grass the cool wind lives

小林一茶

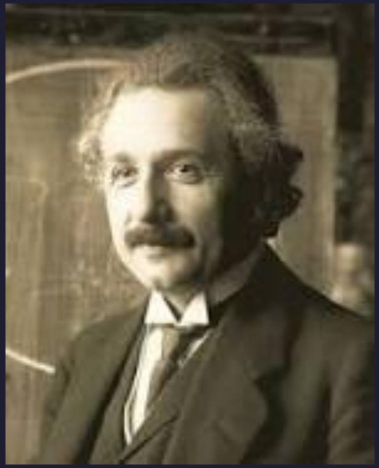
Issa Kobayashi

1814

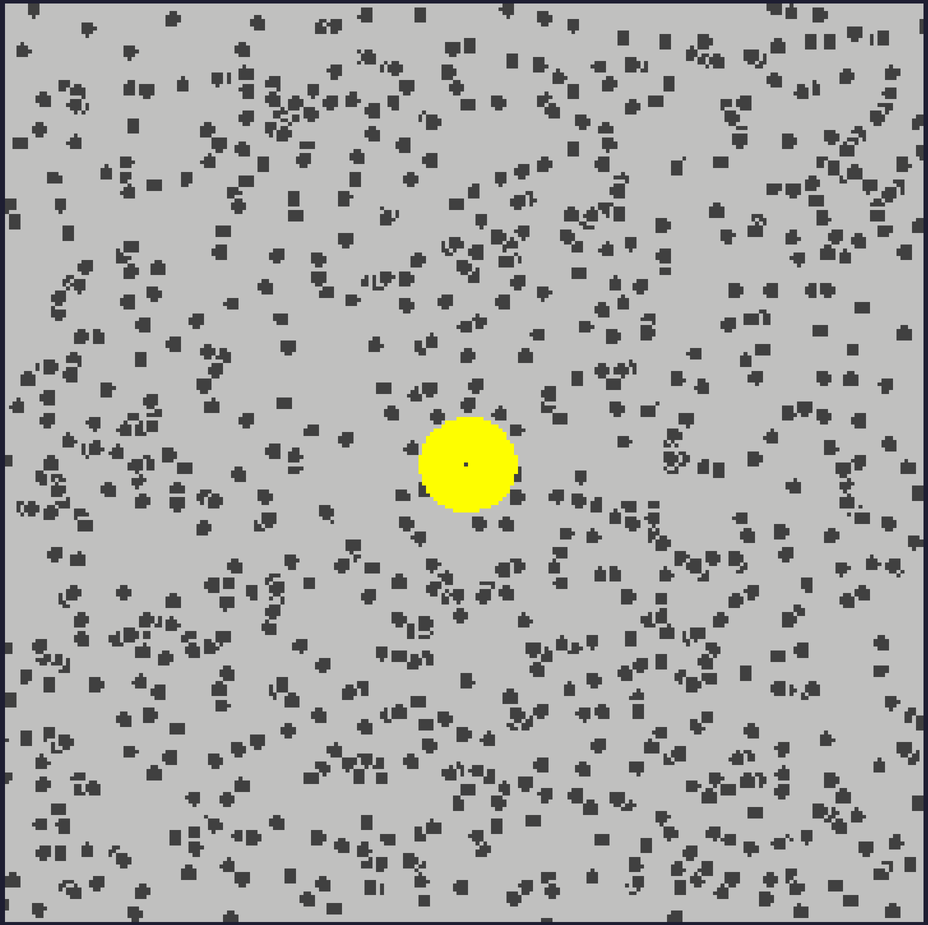
Physicits can feel hot early Universe
13 800 000 000 years ago
in tiny fluctuations of
cosmic microwave



Physicists can feel the existence of microscopic atoms behind random fluctuations of Brownian pollens



A. Einstein
1905



quarks

Feel quarks behind fluctuations
in relativistic heavy ion collisions

2014

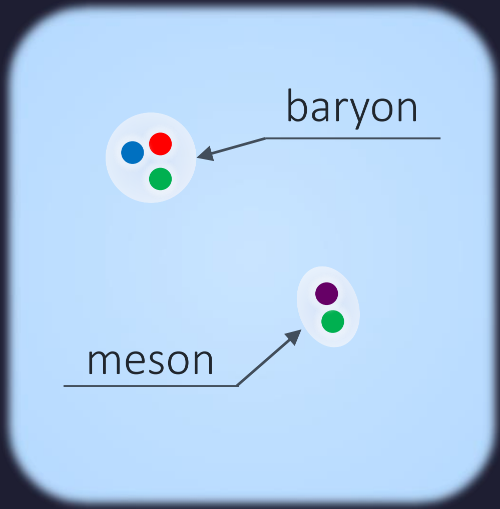
Non-Gaussian Fluctuations in Relativistic Heavy Ion Collisions

Masakiyo Kitazawa (Osaka U.)

Frontiers of Theoretical Science, Kavli IPMU, Nov. 6, 2014

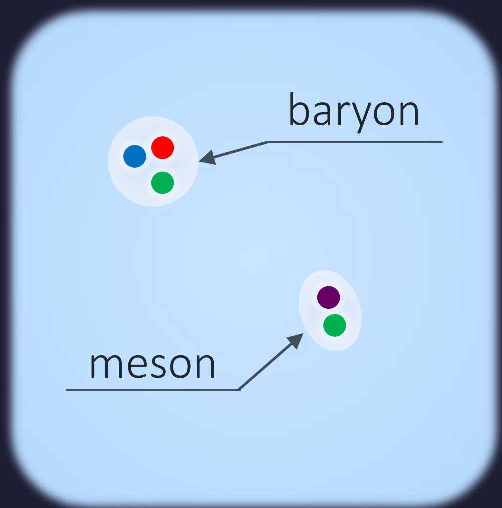
Quark-Gluon Plasma

vacuum



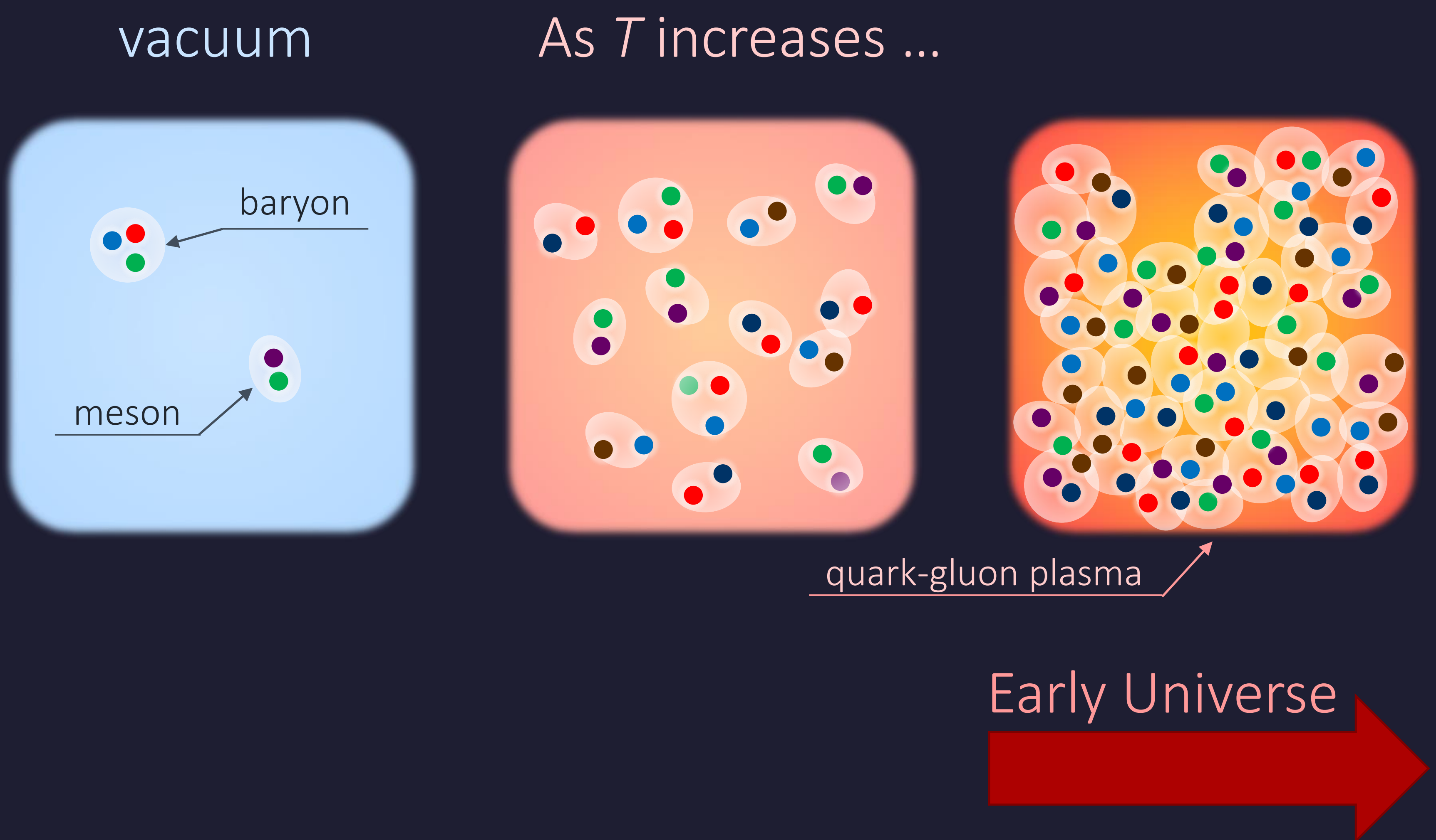
Quark-Gluon Plasma

vacuum

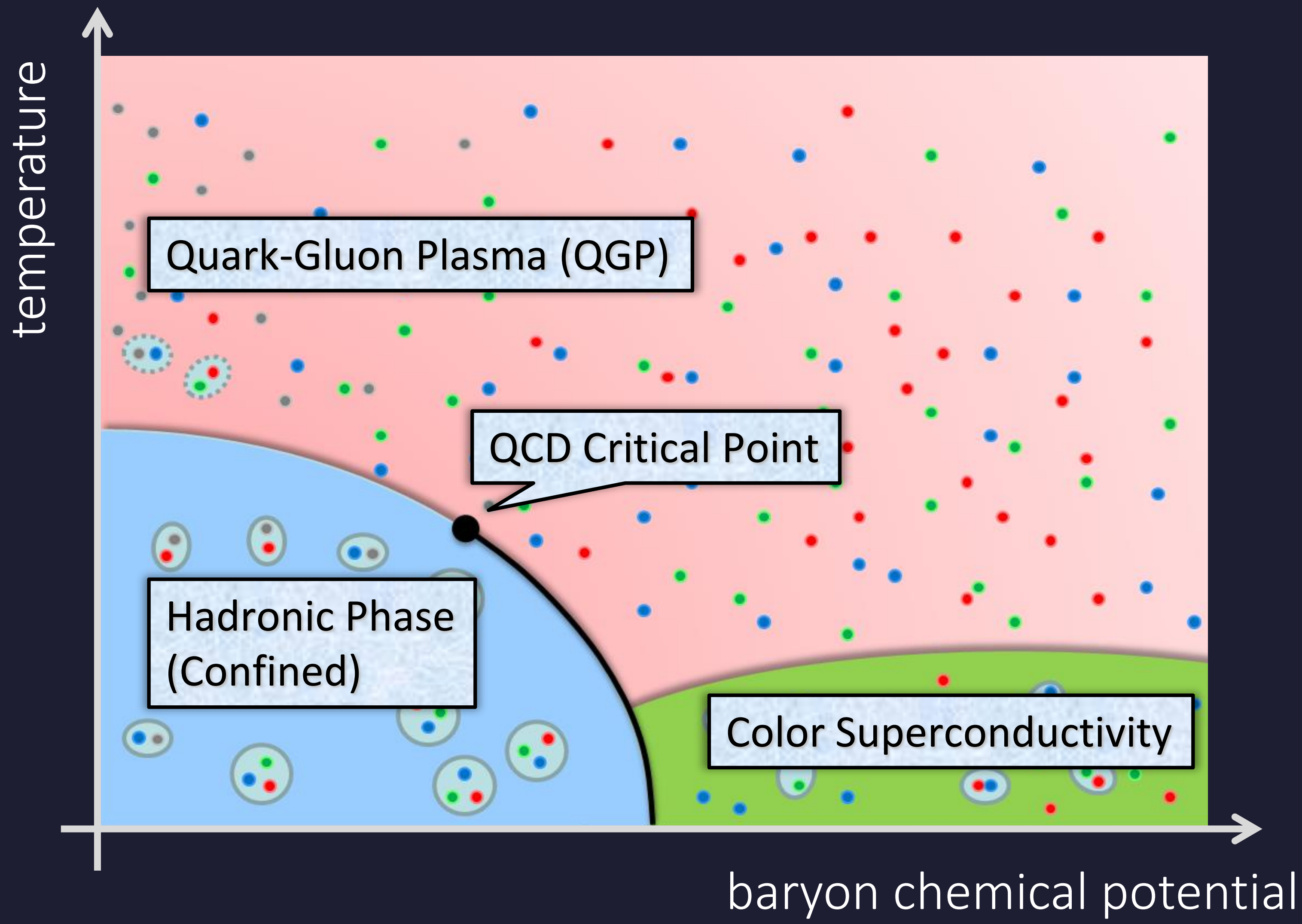


As *T* increases ...

Quark-Gluon Plasma (QGP)

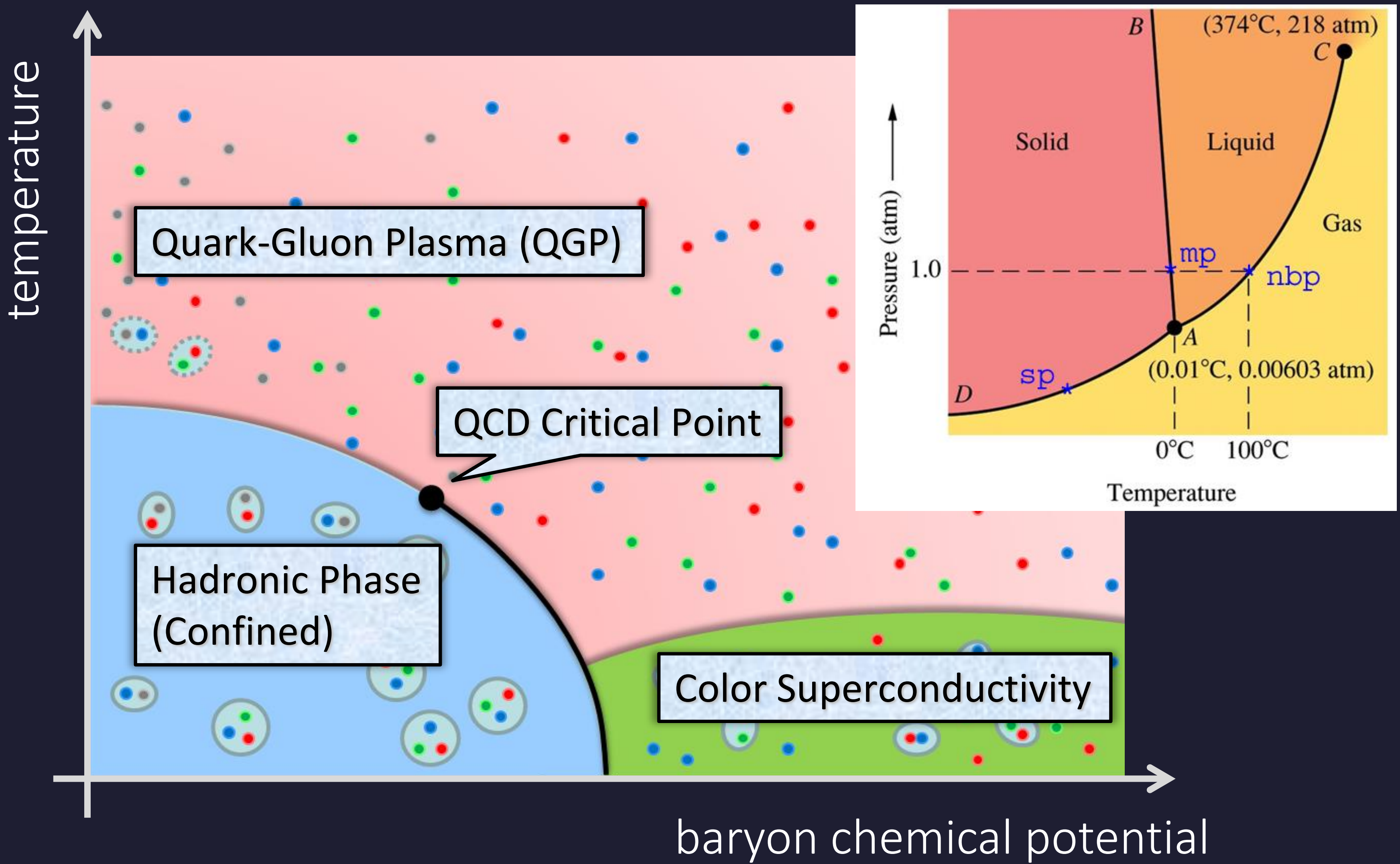


QCD Phase Diagram



QCD Phase Diagram

Phase diagram of water



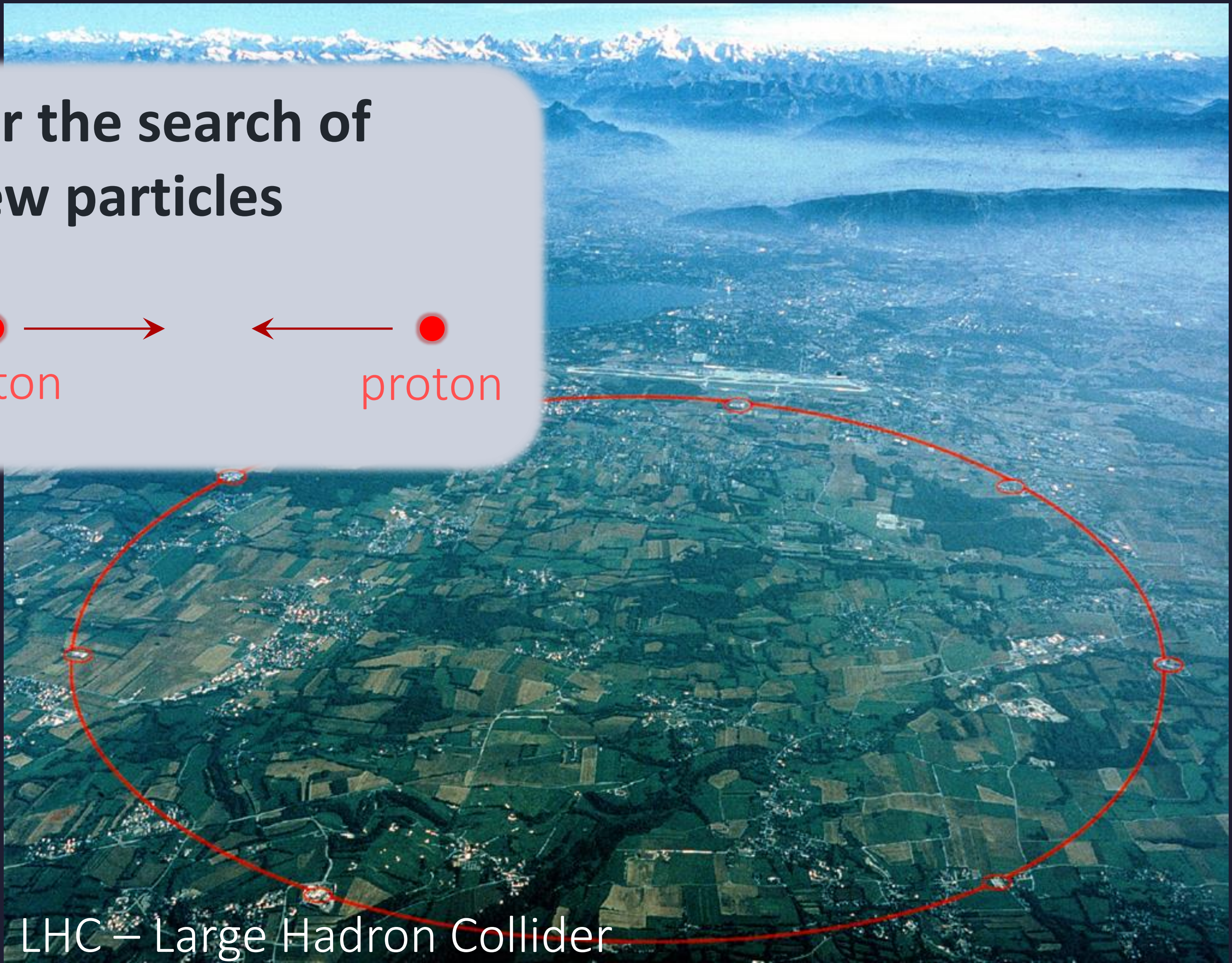
Relativistic Heavy Ion Collisions

LHC – Large Hadron Collider

Relativistic Heavy Ion Collisions

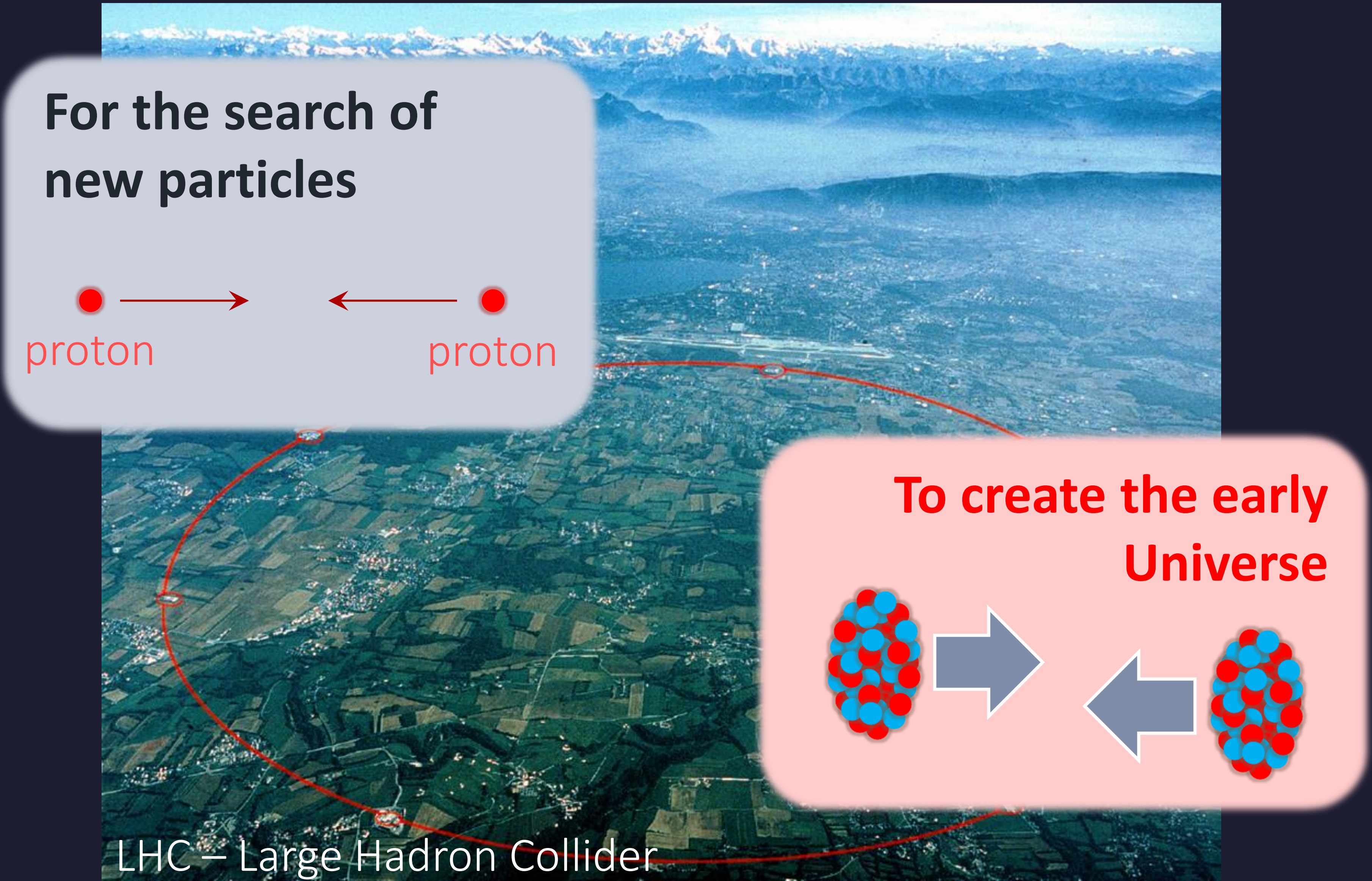
For the search of new particles

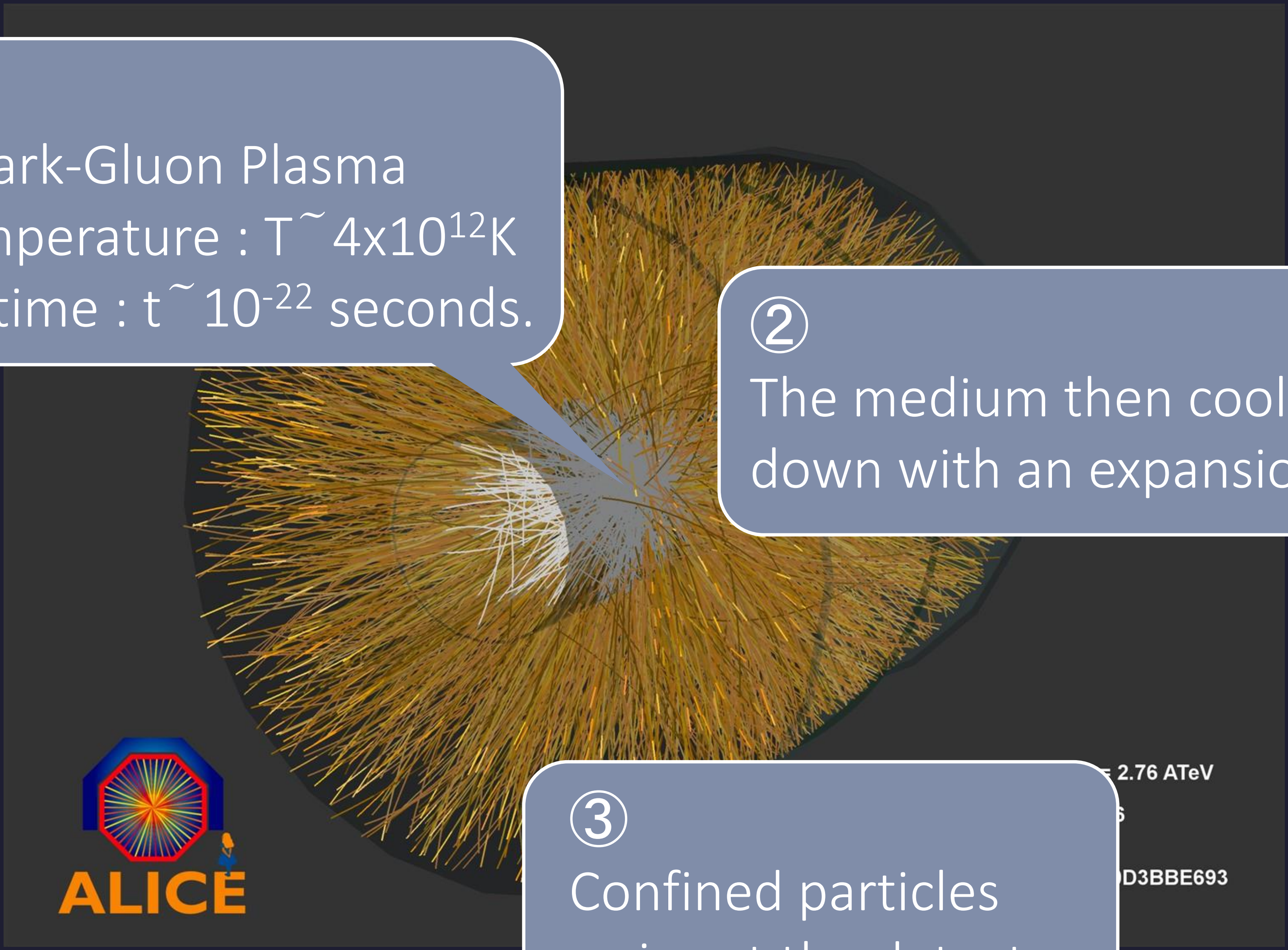
proton → ← proton



LHC – Large Hadron Collider

Relativistic Heavy Ion Collisions





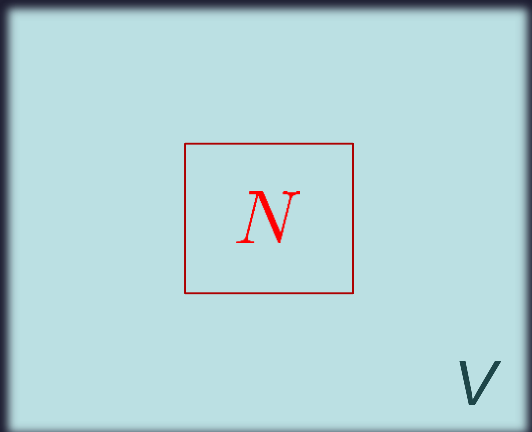
①
Quark-Gluon Plasma
temperature : T ~ 4×10^{12} K
lifetime : t ~ 10^{-22} seconds.

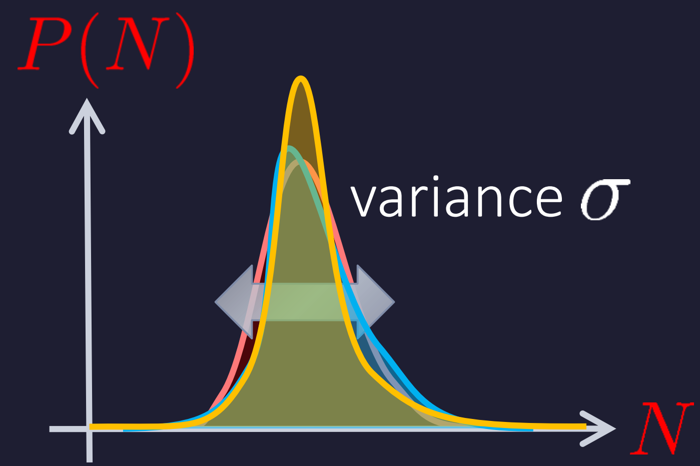
②
The medium then cools down with an expansion.

③
Confined particles arrive at the detector.

Thermal Fluctuations

Observables in equilibrium are fluctuating!





$$\langle \delta N^2 \rangle = V\chi_2 = \sigma^2$$

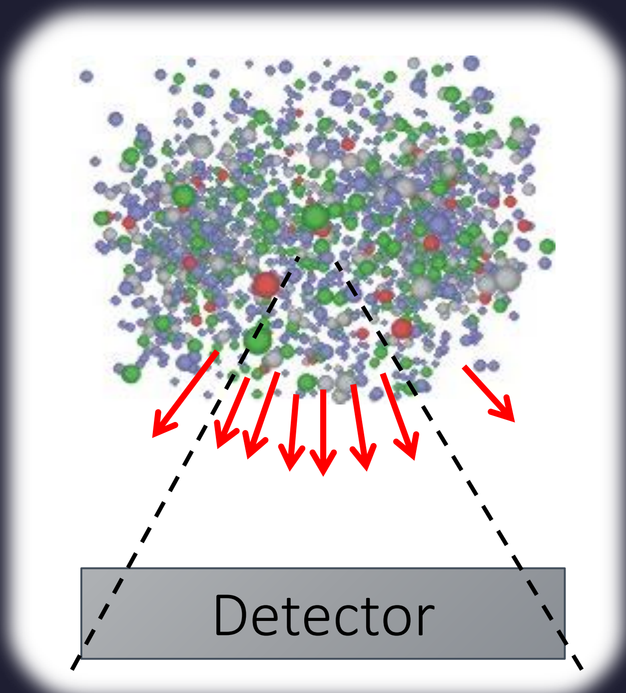
$$S = \frac{\langle \delta N^3 \rangle}{\sigma^3}$$

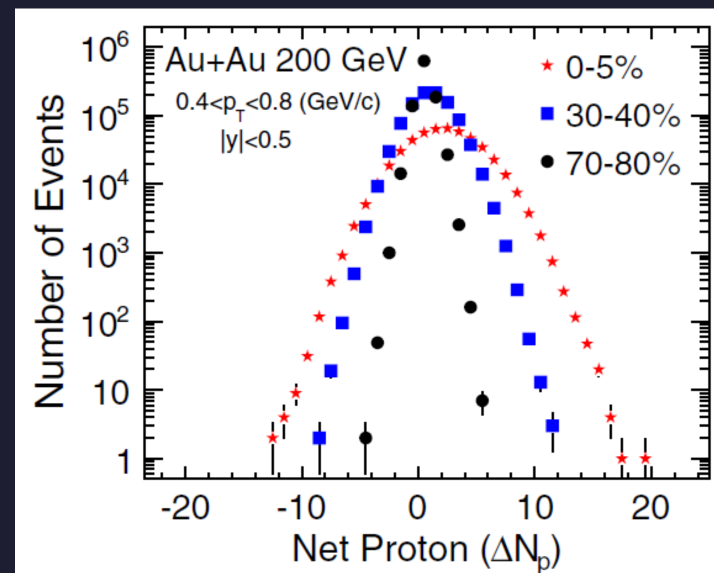
$$\kappa = \frac{\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2}{\chi_2 \sigma^2}$$

Gaussian

non-Gaussianity

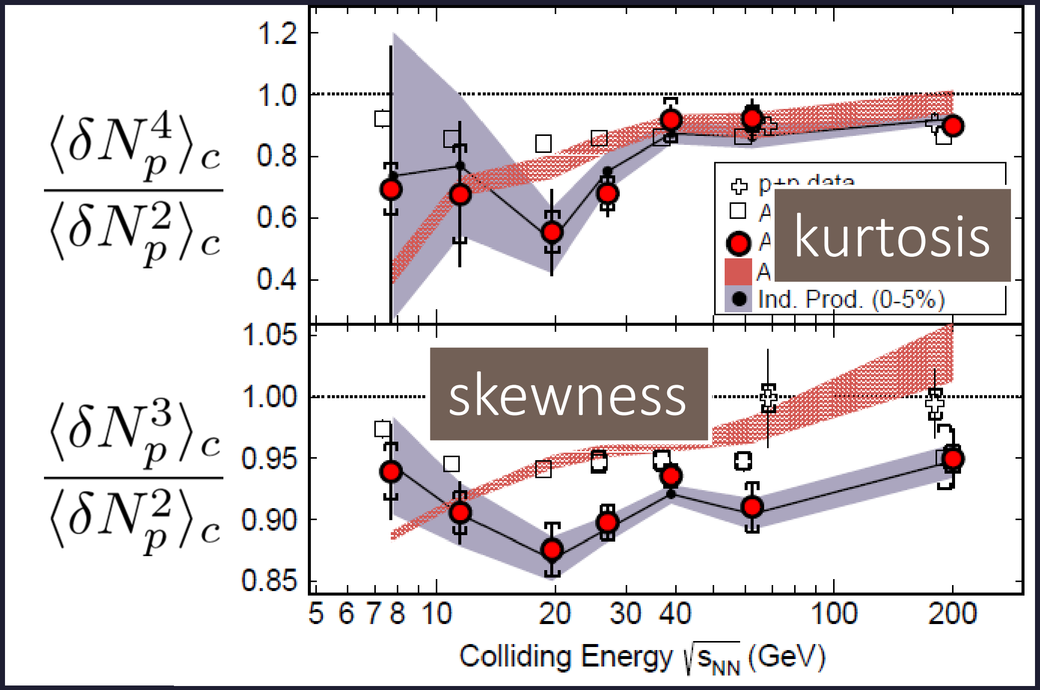
Event-by-Event Measurement



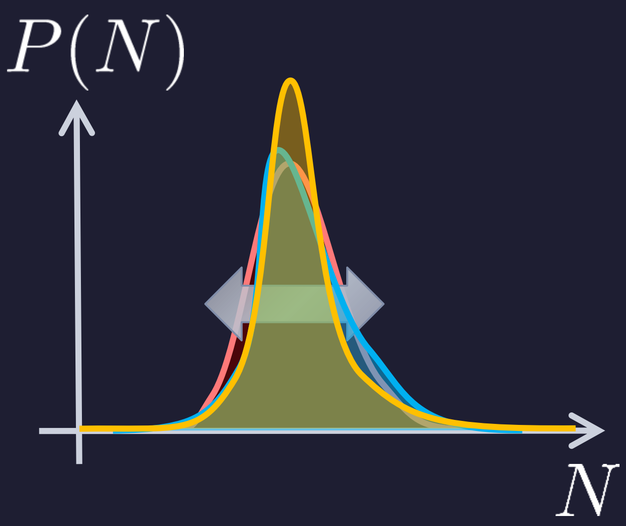


STAR Collaboration, PRL 2010

Non-Gaussianity @ RHIC

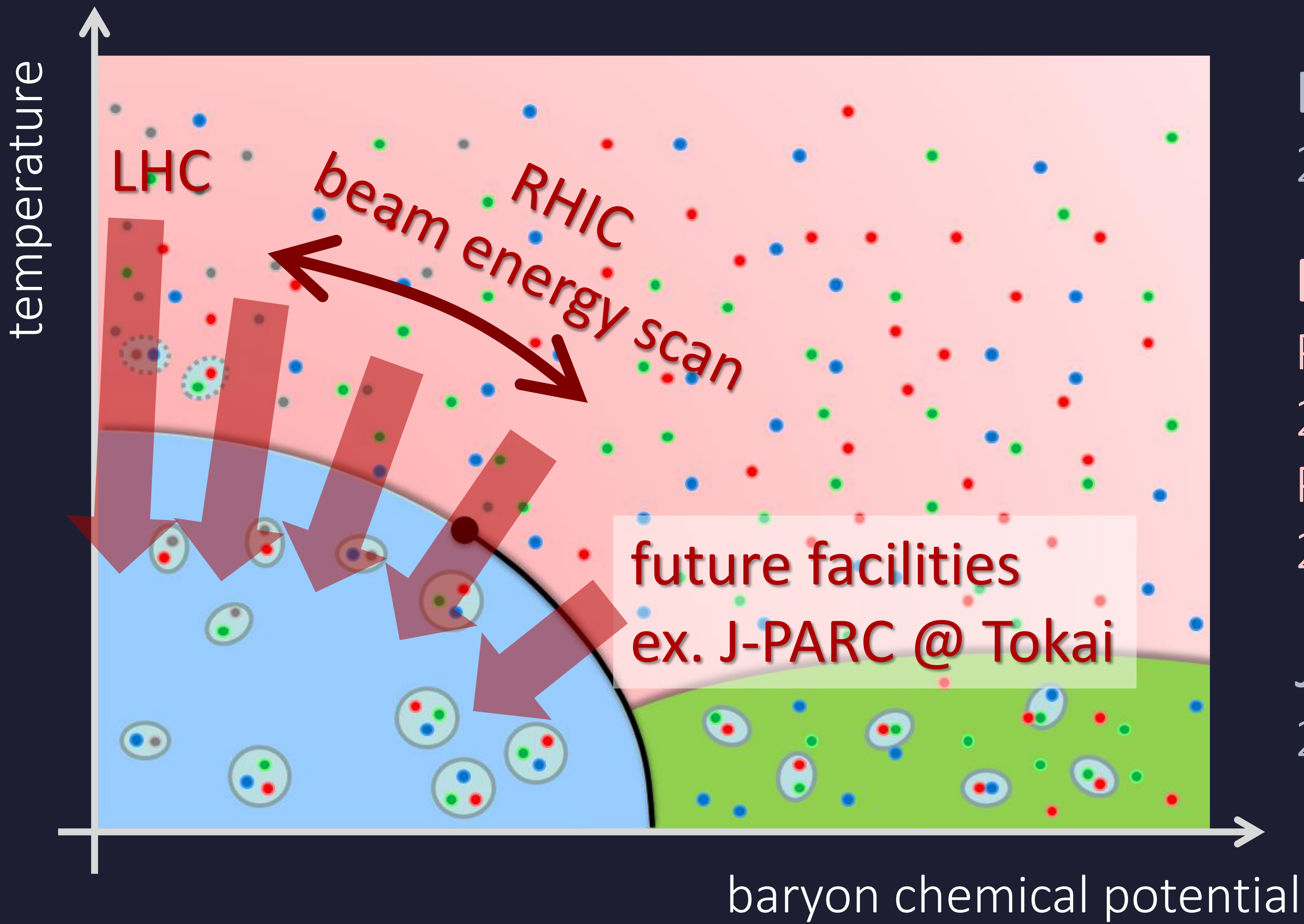


STAR Collaboration, PRL 2014



- Nonzero higher-order cumulants of conserved charges (skewness and kurtosis)
- They are not far from Poissonian values.

Search for QCD Phase Structure



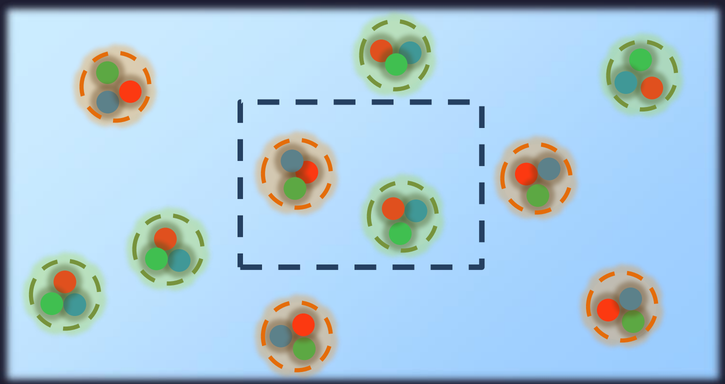
LHC
2010~

RHIC-BES
Phase I
2010~2013
Phase II
2015~

J-PARC
2018~ ??

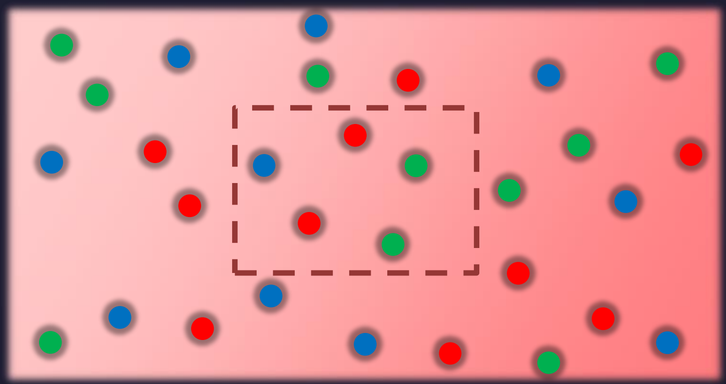
Signal of Quark Deconfinement

Hadronic



$$|q_B| = 0, 1, \ \ |q_Q| = 0, 1$$

Quark-Gluon



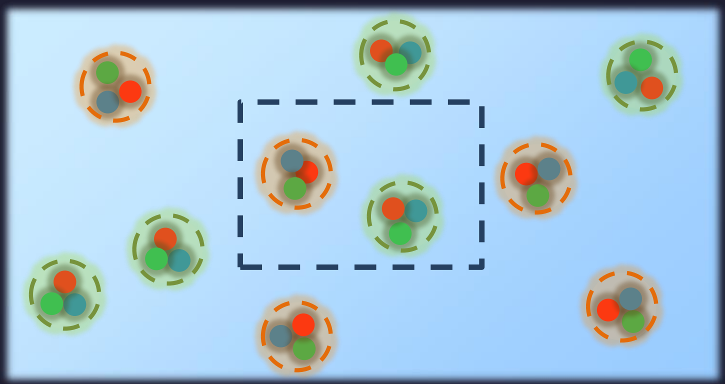
$$|q_B| = 1/3, \ \ |q_Q| = 1/3, 2/3$$

Elemental charge carried by quasi-particles decreases in QGP

Asakawa, Heinz, Muller PRL (2000); Jeon, Koch, ibid.

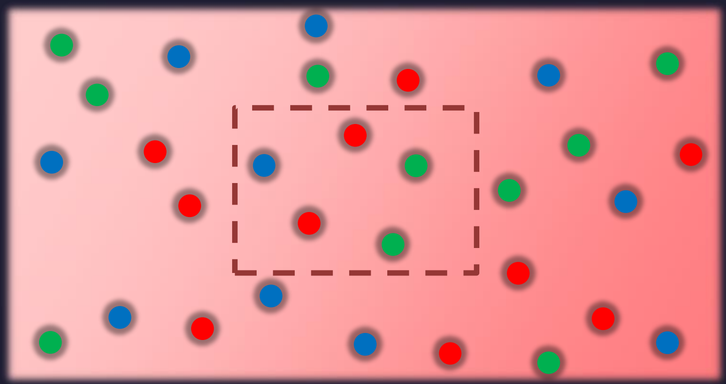
Signal of Quark Deconfinement

Hadronic



$$|q_B| = 0, 1, \ \ |q_Q| = 0, 1$$

Quark-Gluon



$$|q_B| = 1/3, \ \ |q_Q| = 1/3, 2/3$$

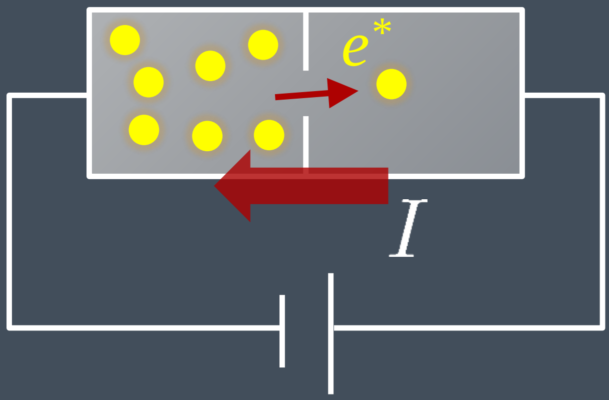
Elemental charge carried by quasi-particles decreases in QGP

⇓

Corresponding thermal fluctuations decrease in QGP

Asakawa, Heinz, Muller PRL (2000); Jeon, Koch, ibid.

Shot Noise

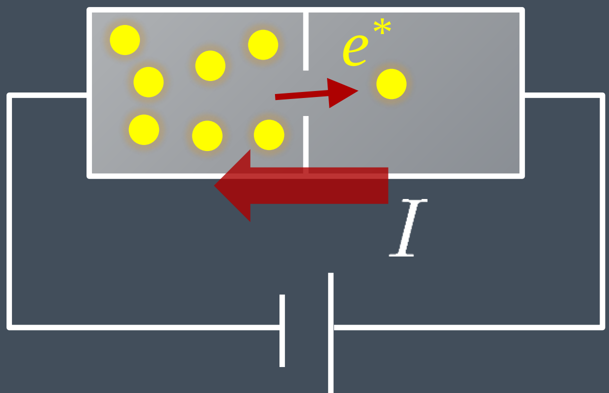


$$S_{\text{shot}} \sim \langle \delta I^2 \rangle$$

$$S_{\text{shot}} = 2e^* \langle I \rangle$$

charge of quasi-particles

Shot Noise



$$S_{\text{shot}} \sim \langle \delta I^2 \rangle$$

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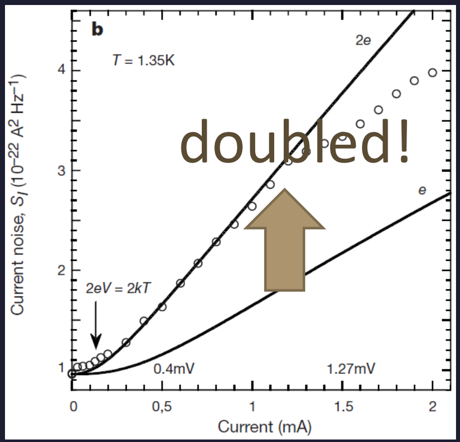
charge of quasi-particles

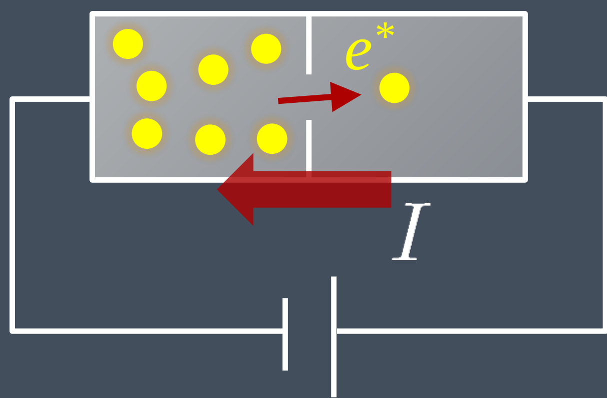
Superconductors with Cooper Pairs

$$e^* = 2e$$

Jehl+, Nature **405**,50 (2000)



Shot Noise



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Superconductors with Cooper Pairs

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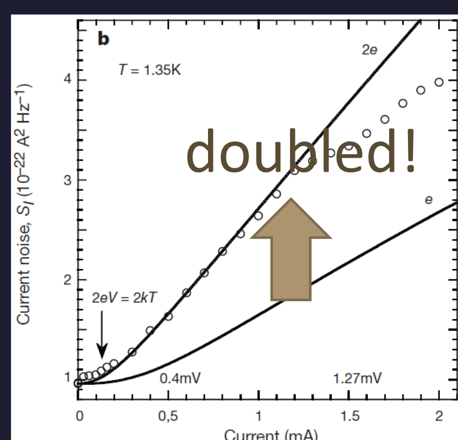
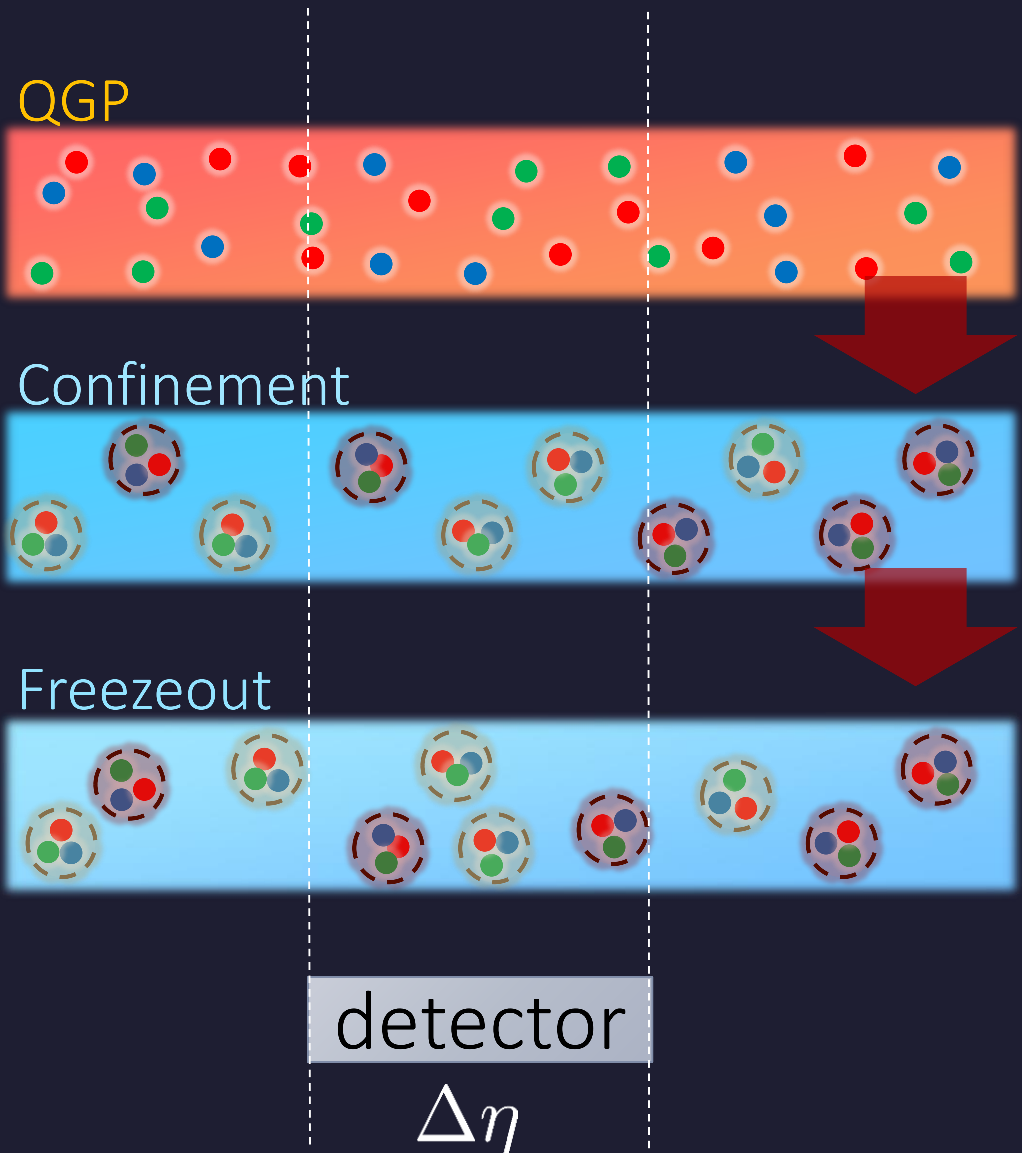


Fractional Quantum Hall Systems

$$e^* = \frac{q}{p} e$$

Saminadayar+, PRL**79**,2526 (1997)

Diffusion of Fluctuations



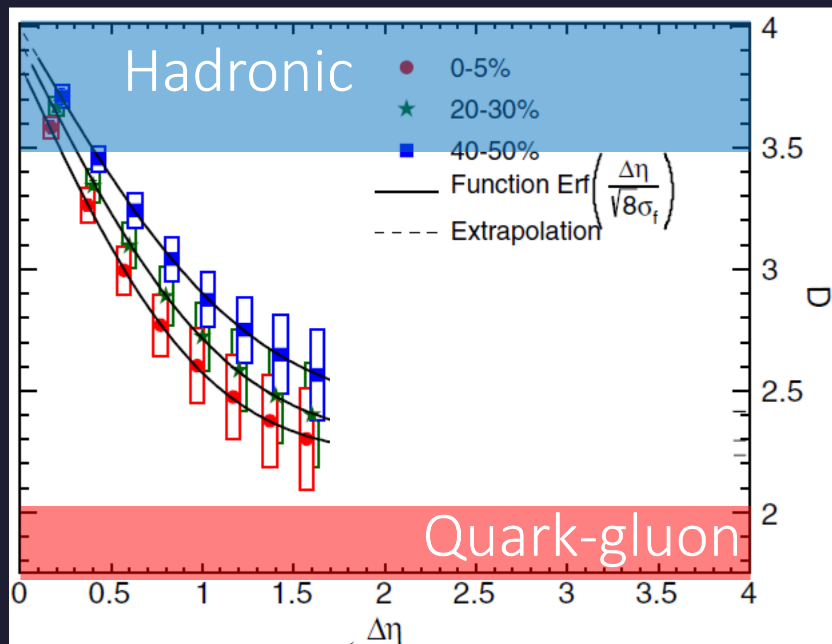
Experiments can vary spatial volume to measure fluctuations

The larger $\Delta\eta$, the earlier fluctuations

Electric Charge Fluctuations @ LHC

ALICE Collaboration,
PRL **110**, 152301 2013

一本の草も涼風宿りけり
一茶



$\sim \frac{\langle \delta N_Q^2 \rangle}{V}$

$\sim V$

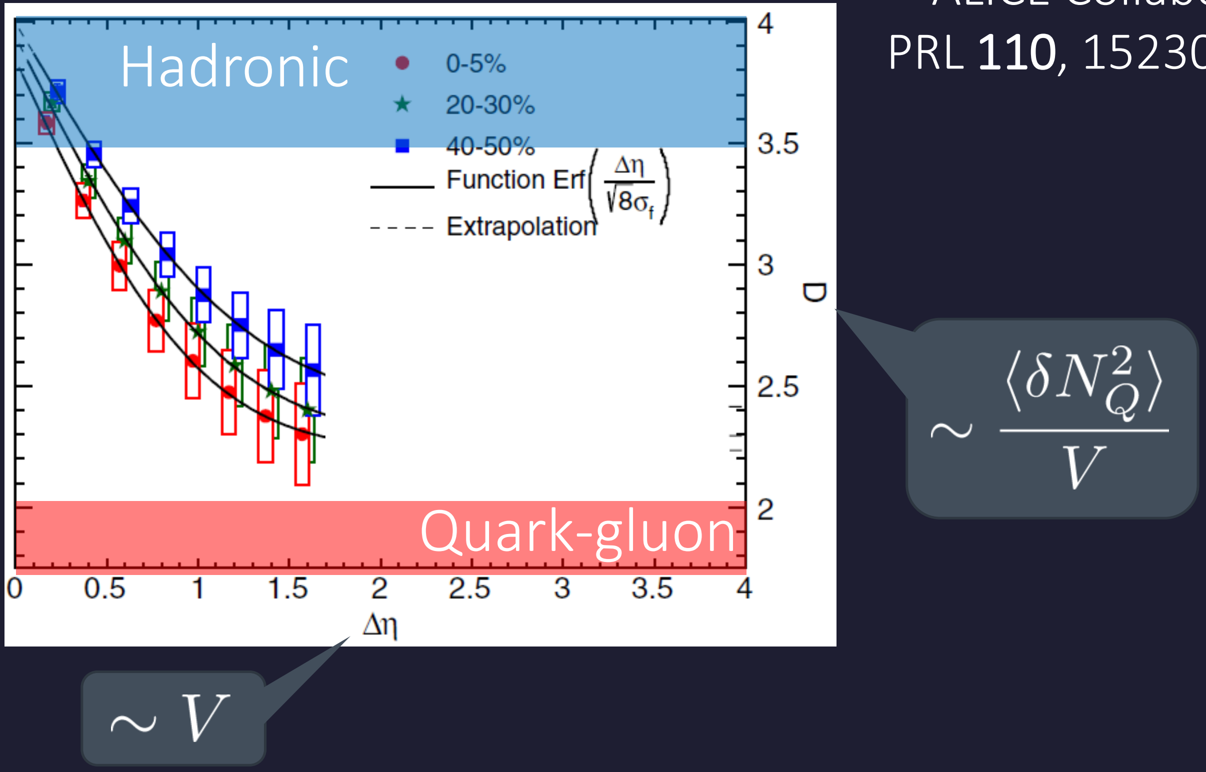
Fluctuation is more QGP-like as *V* becomes larger.
The Δη dependence encodes history of the medium!

Diffusion of non-Gaussianity

MK,Asakawa,Ono,PLB**728**,386(2014)

Electric Charge Fluctuations @ LHC

ALICE Collaboration,
PRL **110**, 152301 2013



- ☐ Experimental results only for 2nd order fluctuation
- ☐ No results on $\Delta\eta$ dependence of higher-order cumulants

Stochastic Formalism

- Fluctuating hydrodynamics (stochastic hydrodynamics)

Landau, Lifshitz, Statistical Mechanics II

- Counterpart for diffusive processes

Stochastic diffusion equation

$$\partial_\tau n = D\partial_x^2 n + \partial_x \xi(\eta, \tau)$$

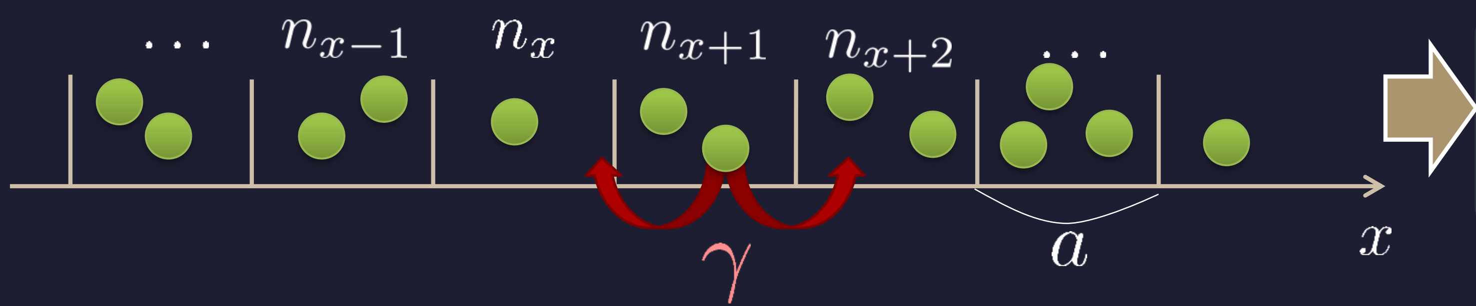
Random force determined by FDR

This formalism cannot describe non-Gaussianity!

Diffusion Master Equation

MK,Asakawa,Ono,PLB**728**,386(2014)

Divide spatial coordinate into discrete cells



probability

$P(\mathbf{n})$

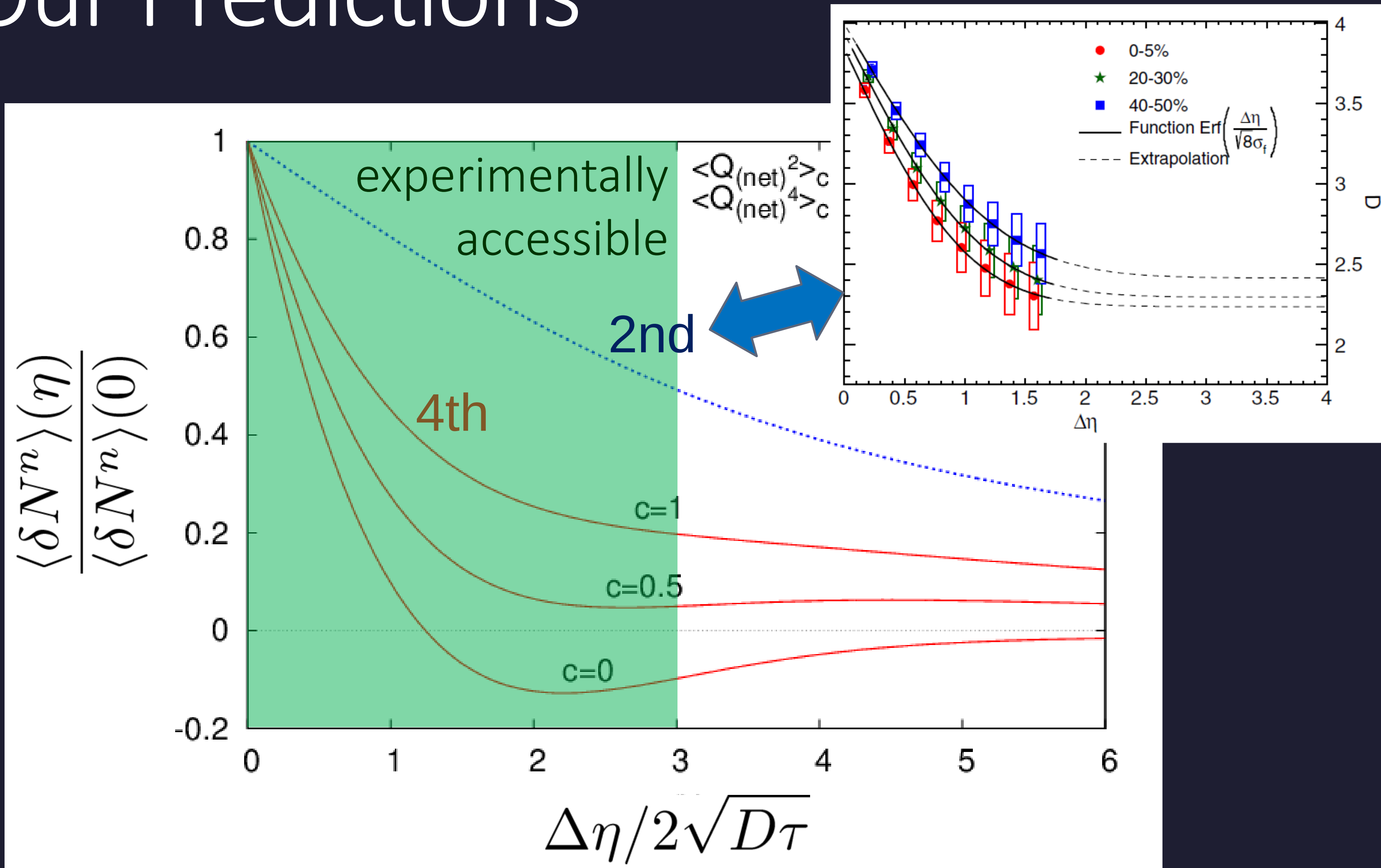
Master Equation

$$\frac{\partial}{\partial t}P(\mathbf{n}) = \gamma\sum_x [(n_x+1)\{P(\mathbf{n}+\mathbf{e}_x-\mathbf{e}_{x+1})+P(\mathbf{n}+\mathbf{e}_x-\mathbf{e}_{x-1})\} - 2n_x P(\mathbf{n})]$$

Solve the DME exactly, and take $a \to 0$ limit

Our Predictions

ALICE Collaboration, 2013



Volume dep. of non-Gaussianity encodes more information!

Summary

- Fluctuations are invaluable tools in physics, as well as in our daily life.

- Fluctuations acquires much attention in relativistic heavy-ion collisions. In particular, their non-Gaussianity is one of the latest topics in this realm.

1998
Rolf Landauer
The noise is the signal

A poet said

一本の草も涼風宿りけり

even on one blade of grass the cool wind lives

小林一茶

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A physicist said

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